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SURFACE X-RAY EMISSION FROM NEUTRON STARS

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ABSTRACT

The surface of neutron stars, if visible at all, will have a temperature of around 10^7 $^{\circ}K$. Most of the radiation from such stars will be in the far ultra violet or the near x-ray band and will not penetrate through our atmosphere. Hence, for the detection of such stars, an orbiting telescope working in the near x-ray band will be most useful.

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Some recent rocketbound X-ray experiments indicated the existence of discrete X-ray sources in the 3Å - 10Å wavelength region[1][2]. The measured flux being 1.4×10^{-8} ergs-sec^{-1}Å^{-1} at 5Å at a source near Scorpius and 2×10^{-9} ergs/cm^{2}Å^{-1} for a source near the Crab Nebula (the remnant of Supernova 1054 A.D.) with a nearly flat spectrum from 1.5Å to 8Å, and an angular size $< 5°$. Detailed spectrum, angular size, shape, and precise locations of the X-ray sources are not yet available.

It was suggested that neutron stars (stars of density $\sim 10^{15}$ g/cm^{3}, thought to be remnants of supernova) are X-ray emitters in the 10Å region, with a total radiative power of around 10^{37} ergs/sec, and will last $\sim 10^{3}$ years[3]. Indeed, if one of the X-ray sources is associated with the Crab Nebula (distance: 4×10^{3} light years) the estimated radiative power is also around 10^{37} ergs/sec[4]. The very high density of neutron stars (~nuclear density), and the very high spatial curvature surrounding them, make them extremely interesting objects. The theoretical importance of whether or not neutron stars are observable has been discussed in a separate paper[3]. In this paper we discuss some properties of the surface pertaining to future experiments.

The internal structure of neutron stars has been widely studied[5]. The general results (independent of the detailed form of any covariant equation of state) are: The mass is in between 0.2 $M_\odot$ to around 1.3 $M_\odot$ ($M_\odot$ = solar mass = 2×10^{33} g); neutron stars with mass outside the above range cannot exist. The radius is around 10^6 cm. Hyperons as well as neutrons may exist if the density is greater than 10^{15} g/cm^3. Since neutron matter is unstable against beta decay when the density is below 10^{12} g/cm^3, the outer shell of a neutron star must be composed of ordinary matter. Most likely, elements are in an equilibrium state; at $\rho < 10^7$ g/cm^3, Fe^{56} is mostly abundant. However, other elements may exist, and their presence may give clues to the history of formation of neutron stars.

We now estimate the energy content, the internal temperature, and the surface properties of neutron stars.

(i) Internal Energy[6]

There are no energy sources inside a neutron star: the radiated energy comes from the remaining thermal energy of the degenerate neutron gas. In stable and realistic star models, the Fermi momentum p_F has a value in between 0.1 $M_n c$ to 0.5 $M_n c$ (M_n is the neutron mass). Using a typical value 0.3 $M_n c$ for p_F, the internal energy E_t of a neutron star is roughly

$$E_t = 3.8 \times 10^{47}\ T_9^{\ 2}\ M_{33}\ \text{ergs} \qquad (1)$$

where $T_n = T/10^n$ and $M_n = M/10^n$.

(ii) Neutrino Production and Internal Temperature

The plasma neutrino process is the most important neutrino process[7]. From the equilibrium electron density in a typical neutron star ($M = 10^{33}$ g/cm^3, radius $R = 10^6$ cm, mean density $\rho = 10^{14}$ g/cm^3) an average neutrino emission rate can be estimated; the results are listed in Table I. The life time against neutrino emission decreases sharply with increasing temperature, and that against optical radiation decreases with decreasing temperature. A maximum time scale ($\sim 10^3$ years) exists at $T \sim 10^9$ ^oK. This we take to be the typical time scale for surface emission from neutron stars.

(iii) Surface Composition and Structure

Matter at $\rho < 10^{12}$ g/cm^3 is composed of beta-stable nuclei and degenerate electrons. At a lower density ($\sim 10^6$ g/cm^3) electrons will be non-degenerate. While the density drops sharply from neutron matter to the non-degenerate layer because the thermal conductivity of degenerate electrons (and neutrons) is very high compared to that of the non-degenerate layer, the temperature is nearly constant throughout the neutron star and drops sharply only in the non-degenerate layer. In this respect, the surface of neutron stars resembles that for white dwarf stars. Also in the surface, the relativity parameter $GM/Rc^2 \approx 0.1$ (R is the radius of the neutron star, G the constant of gravitation; non-relativistic theory may be used. Using the same technique as used in solving white dwarf stars[8], for the degenerate layer one obtains ρ as a function of r:

$$\rho = 4\times10^{13}\left(\frac{M_{33}}{R_6}\right)^3\left(\frac{1}{\xi}-1\right)^{3/2}\left[\left(\frac{1}{\xi}-1\right)+7.4\times10^{-3}\,\frac{M_{33}}{R_6}\right]^{3/2}$$

where $\xi = r/R$, $R_6 = R/10^6$ cm. For $M_{33} = R_6 = 1$, and $\rho = 10^{12}$ g/cm^3, we find $1 - \xi = 0.1$ and the mass contained in the degenerate layer amounts to only 10^{-3} of that of the star.

In the non-degenerate layer, two physical processes contribute to the opacity of matter to radiation: Compton scattering and photo-ionization of K shell electrons of Fe^{56}. The cross-section of Compton scattering at $T = 10^9$ ^oK is still quite close to its non-relativistic value $\left(= \frac{8\pi}{3}\left(\frac{e^2}{mc^2}\right)^2 = 6.7\times10^{-25}\ \text{cm}^2\right)$. The cross section for the photo-ionization process has a ν^{-3} dependence (ν is the frequency of the photon). At $T > 5\times10^7$ ^oK, there are very few bound electrons, and only Compton scattering need be considered. At $T < 5\times10^7$ ^oK, the opacity is predominantly due to photo-ionization process (bound-free process).

We may define the beginning of the non-degenerate layer by using one of the following three criteria: (i) when the perfect gas pressure ($P = \frac{k}{m_p}\frac{1}{\mu_e}\rho T$) is equal to that for a degenerate gas (Eq. (4)), this gives $\rho \sim 10^6$ g/cm^3 at $T = 10^9$ ^oK. (ii) When the thermal conductivity of electron gas[9] is the same as that due to Compton scattering. This gives $\rho \approx 5\times10^5$ g/cm^3. These two criteria give the same value of ρ to within a factor of 2. If the internal temperature T is greater than 5×10^8 ^oK, the temperature drops to within 50% of the surface temperature before photo-ionization process becomes important. The opacity κ for Compton scattering is independent of temperature and density [$(\kappa\rho)^{-1}$ is the mean free path of photons]. The radiative transfer problem becomes analytically solvable[10]. The solution is

$$\rho = \frac{4\pi cGM}{\kappa L} \frac{a\mu_e m_p}{3k} T^3 = \frac{1.92 \times 10^{-18}}{(L/L_\odot)(\kappa/0.2)} M_{33} T^3 \tag{3}$$

$$T = \frac{m_p \mu_e}{3k} GM\left(\frac{1}{r} - \frac{1}{R}\right) = 5.4\times10^{11} \, (M_{33}/R_6)\left(\frac{1}{\xi} - 1\right) \tag{4}$$

where L is the total energy flux, k is the Boltzmann constant, a the Stefan-Boltzmann constant, $L_\odot$ = solar energy flux = 2×10^{33} ergs. For the Compton process, $\kappa = 0.2$. Knowing T and ρ at the beginning of the non-degenerate layer, one can fit Eq. (3) to the interior solution of Eq. (2) using L as the fitting parameter.

At $T = 10^9$ ^oK, the density that separates the degenerate and non-degenerate layer has a value 10^6 g/cm^3. From Eq. (3) we find $L = 2\times10^3 L_\odot$. This value of L may be further checked by noticing that

$$L = \frac{ac}{4} T^4 \, 4\pi R^2/n_s = 7\times10^{44} \, (T_9{}^4/n_s) \text{ ergs/sec} \tag{5}$$

where n_s is the total number of scatterings an average photon suffers before leaving the star, and T is the internal temperature of the star. The proof of Eq. (5) may be found in reference (3). n_s is given by

$$n_s = \int \kappa \rho dr \qquad (6)$$

The integration terminates at roughly the surface temperature of the star. Using Eq. (3), (4) and a more precise value of κ from a detailed Los Alamos calculation[11], one finds $n_s = 1.8 \times 10^8$, of which around 10% is contributed by photo-ionization process. From Eq. (5) we find $L \approx 10^3 L_\odot$, which is only a factor of 2 different from the value we obtained from fitting boundary conditions. As a final check, at a surface temperature of 10^7 $^\circ$K, the integrated central temperature is around 0.8×10^9 $^\circ$K, close to the value of 10^9 $^\circ$K that we assumed.

Table I lists the photon luminosity as a function of the central temperature, surface temperature, and $\tau = T/(dT/dt)$ (lifetime).

As the internal temperature drops to below 10^8 $^\circ$K, the spectrum of surface emission shifts to ultraviolet region for which interstellar absorption is large, and the chance for observation is small.

TABLE I. NEUTRON STAR EMISSION CHARACTERISTICS [12] [13]

Internal Temperature °K	Total Thermal Energy (ergs)	Photon Luminosity ergs/sec	Surface Temperature °K	Lifetime (photon) years	Lifetime (neutrino) years	Wave length of Maximum in Spectrum (Å)
5×10^{9}	10^{48}	5×10^{37}	1.7×10^{7}	7×10^{3}	1	1.9
2×10^{9}	1.6×10^{48}	2×10^{37}	1.3×10^{7}	3×10^{3}	10^{2}	2.5
10^{9}	4×10^{47}	8×10^{36}	1.1×10^{7}	1.7×10^{3}	10^{3}	3
5×10^{8}	10^{47}	2.8×10^{36}	0.8×10^{7}	10^{3}	$\gg10^{3}$	4.1

Model Mass = 10^{33} g; Radius = 10^{6} cm.

(iv) Spectrum of Surface Emission of Neutron Stars

Although the energy output of a neutron star is high, only a small fraction of it ($\sim 10^{-3}$) will be able to penetrate through our atmosphere(14), and most of the emission will be in the X-ray region. The mean surface density is around 0.1 g/cm^3. With a value of $\varkappa = 2.6$ at $T = 10^7$ °K (photo-ionization process) most of the emission will come from a layer of thickness around 4 cm (~ the mean free path of photons). The spectrum will show absorption lines or discontinuities at the ionization energy of K or L electrons, with a Doppler width of around $10^{-3}\lambda$. From the location and magnitude of more than one of these discontinuities (or lines) one can determine the red shift and the composition.

The red shift is of the order of $\frac{GM}{Rc^2}$ (~0.1) and is quite large compared with the Doppler shift caused by the motion of heavenly bodies ($\frac{v}{c} \sim 10^{-4}$). The red shift is proportional to M/R. On the other hand, if we can obtain a good, reliable equation of state from elementary particle theory, we can obtain a theoretical M-R relation. Combining this result with the red shift measurement, the mass of neutron stars can be determined. The surface temperature and the measured flux on earth, combining with an information on R, will give us a distance, which can be checked against known distances of supernova remnants, if any. Presently, the measurable flux in rocket technique is around 10^{-8} ergs/sec-cm^2. This means that neutron stars at a few thousand light years can now be detected. In the future, when space observatories are available, it is not beyond the present technology to detect all neutron stars (age ≈ 1000 years) in our galaxy. Since at 10Å wavelength, interstellar absorption is negligible, one can even detect those behind dust clouds. Supernova explosions obscured by dust clouds may now be observable in the X-ray band, since during the first year of the formation of neutron stars, they have an X-ray luminosity equivalent to 10^4 $L_\odot$ (Table I).

Moreover, because the life time of neutron stars against optical radiation is short, one can observe annual declines in the energy flux as well as a decrease in temperature. One can get great sensitivity by observing the tail of the Planck distribution (say, observe 10 kev photons for 1 kev surface temperature.)

The rate of occurence of supernovae is around one per 50 → 300 years. Hence the maximum number of experimentally observed neutron stars X-ray sources anticipated cannot exceed, say, 50. At present, only three discrete sources have been resolved(1)(2).

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REFERENCES

1. H. Gursky, R. Giacconi, F. R. Paolini, and B. Rossi, Phys. Rev. Letters 115, 30 (1963)

2. H. Friedman, paper presented in Astronomical Society Meeting December, 1963 (Washington, D.C.) (To be published).

3. H. Y. Chiu, "Supernovae, Neutrinos, and Neutron Stars", to be published in Annals of Physics.

4. Near the source located in Scorpio (to within one degree), a very bright star of brightness ~ quarter moon was observed for four months around A.D. 827 by two Arabic observers, Haly and Giafar Ben Mohamed Albumazar. No similar records have been located in Chinese or Japanese history yet, but this event deserves attention. For, if this event were a supernova, from its brightness description, its distance will be around 1/3 of that of the Crab Nebula from us, and the X-ray emission of this would-be neutron star will be around ten times stronger than that from the Crab Nebula — a fact indeed observed.

5. Other references on neutron stars may be found in Ref. (3).

6. For the thermodynamic properties of a Fermi gas, see S. Chandrasekhar, "An Introduction to Stellar Structure", Chapter X, (Dover, 1951)

7. B. Adams, M. Ruderman, and C.-H. Woo, Phys. Rev. 129, 1383 (1963) Other neutrino processes give a rate a few orders of magnitude below that discussed in this paper.

8. Ref. (6), Chapter XI.

9. K.S. Singwi and M. K. Sundaresan, Proc. Phys. Soc. London, Sect. A., 64, 29 (1951)

10. Ref. (6), p. 292

11. A. Cox, "Stellar Envelope Coefficients and Opacities", Los Alamos Laboratory pre-print (unpublished).

12. When this paper was finished, the author leared that Dr. D. Morton (to be published) obtained results similar to that given in Table I. However, Dr. Morton did not obtain the neutrino life time.

13. R. Stabler (Cornell thesis, 1960, unpublished) has first considered the observable features of neutron stars. However, he used a simplified form of bound-free opacity (Kramer's Law) all throughout the calculation, and he obtained a surface temperature ~ 3 times lower than that obtained in this paper. Kramer's Law is not applicable to the surface of neutron stars.

14. E. E. Salpeter, "Superdense Equilibrium Stars", reported in the Dallas Conference on Gravitational Collapse, held December 16-18, 1963. Proceedings to be published. Visible part of the Planck spectrum at $T \sim 10^7$ °K is around 10^{-8} of the total energy output, but a large fraction of ultraviolet light ($\sim 10^{-3}$) can be converted into visible light by interstellar gas surrounding the neutron star.